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Gas ionization by focused laser beams

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Abstract

It is shown that the effect of line broadening by focusing may considerably contribute to the observed laser-induced ionization of gases when the ionization energy of the gas molecules is well above the mean photon energy of the laser radiation. (Author)

1. Introduction

Ionization of gases induced by laser radiation has been observed even in those cases where the ionization energy of the gas molecules is well above the mean photon energy of the radiation. Panarella (1) has pointed out that the existing multiphoton and cascade theories attempting to account for the effect actually are in serious divergence from experiments. He has, therefore, put forward and "effective-photon hypothesis" which assumes that the energy distribution of the photon broadens when the intensity of the radiation beam increases (2). In a previous paper (3) we have shown that focusing of a classical quasi-monochromatic light beam also leads to line broadening and that the "effective-photon hypothesis" of Panarella might thus be avoided. In (3) we restricted ourselves to showing that the effect exists, but we considered only frequencies in the vinicity of the line center. In this paper we consider the frequencies far apart from the line center as is necessary for ionization, and we show that the effect may considerably contribute to the ionization of gases by laser radiation and may reduce the difficulties in multiphoton and cascade theories. Since little seems to be known experimentally about the line shape in these faroff regions, we try some functions that appear reasonable. The effect depends crucially on this choice. Good results are obtained with an exponentially damped Lorentzian form.

2. The Ionization Formulas

Basically our explanation is the following. The radiation beam has a line profile, i.e., an energy distribution, $P(\omega)$. $P(\omega)d\omega = |\psi(\omega)|^2 d\omega$ is the probability of getting a photon energy in the interval $\hbar\omega \ldots \hbar\omega + \hbar d\omega$, and $\int_0^\infty P(\omega)d\omega = 1$. The probability for getting a photon energy above the ionization energy W then is

$$[1] \qquad Q(W) = \int_{W/\hbar}^{\infty} P(\omega)d\omega$$

and from the normalization of $P(\omega)$ we have

$$[2] \qquad Q(0) = \int_0^\infty P(\omega)d\omega = 1$$

Now, the line width $\Delta\omega$ of a beam emitted from a laser usually is very small compared to the center frequency ω_0 so that Q(W) is also very small when the ionization energy

W is well above $\hbar\omega_0$, i.e. above the mean photon energy. However, when the beam is focused, the line width broadens, according to our previous paper (3) (see below), and Q(W) increases considerably, as illustrated in Fig. 1. We consider the beam to consist of single pulses. Let each pulse contain

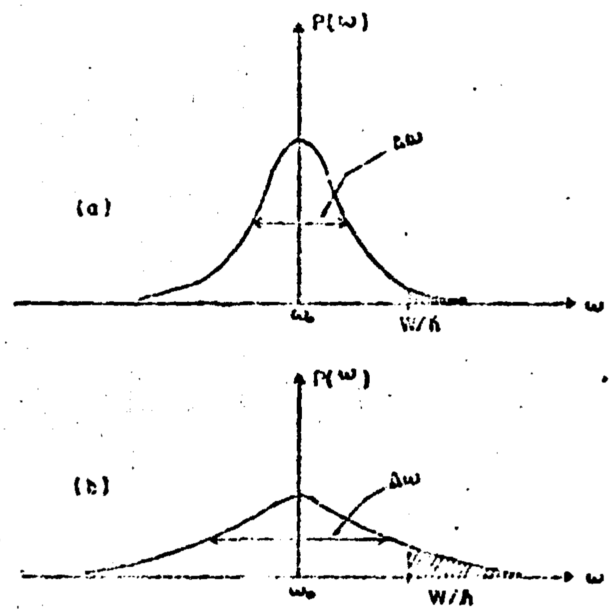

Fig. 1 Sketch of the line broadening by focalization. (W= gas ionization potential)

(a): Beam before passing through the lens.

(b): Beam after passing through the lens.

an average number of N photons. The average number of those photons in a pulse which have energies above W is then N x Q(W), and these photons can ionize the gas atoms. We here assume that only photons from one and the same laser pulse can cooperate in effecting the observed ionization phenomena but not photons from different pulses because the time between successive pulses usually is long enough for recombination to restore the initial situation. In order to ionize one atom it is thus necessary to have

$$[3] \qquad N \times Q(W) \geq 1$$

If we leave fluctuations in N out of account formula [3] gives the threshold for ionization to occur. This ionization is not necessarily observable ionization, for instance in the form of optical breakdown or of spark production, a number of ions larger than 1 is required. This number depends on factors like gas pressure, temperature etc., in a complicated and often unclear way. We do not wish here to deal with these complications and take all situations where we have $N \times Q \geq 1$ as worth being considered. In table I we present the actual numerical values obtained for N x Q in the various cases so that reader can draw his own conclusions.

The relation between the focusing angle α of an axially symmetric beam and the line width $\Delta\omega$ was derived in (3) by calculations on a classical wave pulse, whose transverse spreading represents the divergence of the beam. The ionization is then considered in a semi-classical way in the sense of Einstein's light quantum explanation of the photoelectric effect. The result of the calculations in (3) to a good approximation under the conditions of the actual experiments was

$$[4] \quad \left(\frac{\Delta\omega}{\omega_0}\right)^2 = \left(\frac{\Delta k_y}{k_0}\right)^2 \left\{1-2\sin^2\alpha\left[1-\frac{1}{2}(3\chi+1)\sin^2\alpha+\chi\left(\frac{\Delta k_y}{k_0}\right)^2\right]\right\}+$$

$$+\frac{1}{2}(\chi-1)\sin^4\alpha\{1-2\eta\sin^2\alpha\}$$

where χ and η are parameters whose values depend on the line shape. In view of the many uncertainties and unknowns in the situations under discussion we here use the simplified version

[5] $$\frac{\Delta\omega}{\omega_0} = \left[\frac{1}{2}(X-1)\right]^{1/2} \sin^2\alpha$$

which can be shown to be justified under the conditions of the experiments with which we compare our results (for more details see (3)). Another drawback of the complicated formula [4] is that it can lead to negative values for $(\Delta\omega)^2$ for angles α satisfying $\sin\alpha \gtrsim (2\eta)^{-1/2}$. This defect is absent in the lower approximation [5] and would also disappear if we went to higher approximations in [4]. Formula [4], in the cases where it can be applied, gives somewhat lower values for $\Delta\omega$. Nevertheless, even with [4] we obtain $N \times Q = 5 \times 10^3$ with the realistic values $\hbar\omega_0 = 3.6$ eV (second harmonic of ruby radiation), $W=12.0$ eV (Xenon), $\alpha=10^0$, $N=10^{22}$ and using the same procedure that led to the results in Table I below. The price we have to pay in using [5] is the larger error. Formula [5] (as well as [4]) is the more unaccurate the larger the angle α. The error in the case of the angles met in the experiments may be as large as 50% or more, but this is still small compared with other uncertainties.

As possible forms for the line shape $P(\omega)$

we have considered an exponentially damped Lorentzian distribution in x

[6] $$P(\omega) = (2\Delta\omega f(\varepsilon))^{-1} \cdot \frac{\exp(-\varepsilon x)}{1 + x^2}$$

where

[7] $$x = \frac{\omega-\omega_0}{\Delta\omega}$$

and also a Gaussian and a hyperbolic secant distribution. The Gaussian and hyperbolic secant distributions gave by far too small values of N x Q while the exponentially damped Lorentzian distribution [6] gives reasonable results, as we will show below. A Lorentzian line shape can be derived in quantum theory (4). It does, however, not fit into our treatment in (3) because for a Lorentzian distribution the integrals for the higher moments diverge. Therefore we multiplied the Lorentzian distribution by an exponential in order to force the integrals to converge.

The parameter χ in [5] for the damped Lorentzian distribution is not known exactly. The values given in (3) for χ refer to a damped Lorentzian distribution for the momentum components k_x, k_y and k_z and not for the energy (angular frequency) ω. The relation between the distributions for k_x, k_y, k_z and that for ω is difficult to calculate. Therefore, in the spirit of the pilot nature of our study we just take over the value for χ from (3). The range of values in (3) for $\varepsilon = 0.2 \ldots \infty$ is anyway limited to $\chi = 18.8 \ldots 6$.

The parameter ε in [6] gives the strength of the exponential damping. Table I shows that in 16 different cases we obtain $N \times Q \geqslant 1$ for $\varepsilon = 0.2$. A smaller value for ε would give still higher values of $N \times Q$ but on the other hand would also increase the error contained in formula [5] (for details see (3)).

With the exponentially damped Lorentzian distribution [6] inserted in [1] we obtain

[8] $$Q = (2\varepsilon X^2 f(\varepsilon))^{-1}\exp[-\varepsilon X]$$

where

[9] $$X = \frac{W - \hbar\omega_0}{\hbar\Delta\omega} ,$$

and

[10] $$f(\varepsilon) = Ci(\varepsilon)\sin\varepsilon - si(\varepsilon)\cos\varepsilon$$ (Ref. 5)

and $\Delta\omega$ is given by [5] with $\varepsilon = 0.2$, $\chi = 18.8$. Formula [8] is an approximation for large X, but for $X \geq 50$, which is the range met in the experiments, the error is smaller than 10^{-5}%.

3. Comparison with the Experiments

We have found 23 experimental situations (6-20) in which ionization of gases by focused Laser radiation has been observed in the form of gas breakdown and spark production. The ionization energy was always higher than the mean photon energy by a factor of 7 or more. With the values of W, ω_0, a and N of the respective experiment our formula [8] gave $N \times Q \geq 1$ in 16 cases; these are summarized in Table I. The actual values of $N \times Q$

TABLE I. Values of $N \times Q$ for the exponentially damped Lorentzian with $\varepsilon = 0.2$, $\chi = 18.8$, using the experimental data (6-13), in formulas [5], [8] and [9]

Ref.	Gas	Ioniz. Energy V(ev)	Laser ang. freq ω_0(ev)/$\hbar$	Focaliz ang. α(°)	No. of photons in one pulse(N)	[9] X(ε=0.2)	Criterion(N×Q≫1) N×Q
6	Krypton	14.0	1.8	10.6	$\sim 10^{22}$	65.7	8.2×10^{12}
7	Xenon	12.1	1.8	"	"	59.3	9.4×10^{12}
8	Argon	15.7	"	"	"	75.6	1.2×10^{11}
9	Air	14.0	1.2	12.0	$\sim 10^{20}$	53.2	1.2×10^{10}
10	Argon	15.7	1.2	11.5	"	100.7	4.0×10^{7}
"	Neon	21.6	"	"	"	141.7	5.4×10^{3}
"	Helium	24.0	"	"	"	158.3	1.6×10^{0}
"	Air	14.0	"	"	"	58.9	5.3×10^{9}
11	Air	14.0	1.8	9.2	$\sim 10^{21}$	67.1	8.1×10^{9}
"	Argon	15.7	"	"	"	93.3	5.5×10^{8}
12	Air	14.0	1.2	5.6	$\sim 10^{20}$	100.0	1.2×10^{9}
13	Helium	24.2	1.2	14.3	$\sim 10^{20}$	104.5	1.7×10^{6}
"	Neon	21.6	"	"	"	92.7	2.3×10^{6}
"	Argon	15.7	"	"	"	65.9	9.9×10^{10}
"	Krypton	14.0	"	"	"	58.2	5.9×10^{9}
"	Xenon	12.1	"	"	"	49.5	4.6×10^{10}

ranged from 1.2 to 9.4×10^{12}.

The value of 9.4×10^{12} for the number of photons in a laser pulse which are capable of ionizing the gas seems high enough to justify our clain that the effect to line broadening by focusing has to be taken into account. Even a reduction of that number by several orders of magnitude, due to some possible unjustified assumptions in our work, would still leave us with a huge number.

There are cases of observed ionization where our mechanism does not give an adequate explanation: In 6 cases (14-19) we do not get $N \times Q \geq 1$. The convergence angles in these experiments were as small as $0.3^o ... 3.4^o$ so that we may say there is ionization with effectivelly no focalization. In one case (20) where we do not get $N \times Q \geq 1$ the ionization emergy was a factor of 100 above the mean photon emergy. In (13) and (21) a nonlinear variation of the number of ions created as function of laser power was measured whereas our formula [3] suggests a linear variation, N being proportional to the laser power.

We thus do not say that line broadening by focusing replaces the multiphoton and cascade theories in explaining the observed phenomena, rather it complements them. We expect that our line broadening will reduce the difficulties in the cascade and multiphoton theories of laser-induced ionization of gases, provided the line shape far from the center shows only a limited fall off as, for example, the Lorentzian form.

Acknowledgment

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1. E. Panarella, Phys. Letters 27 A, 657(1968); Lett. N. Cim. 3, 417(1972); Phys. Rev. Lett. 33, 950(1974); Can. J. Phys. 54, 1815(1976); Found. Phys. 7, 405(1977); Phys. Rev. A 16, 672(1977); Bull. Am. Phys. Soc. 23, 914(1978); Proc. of the Int. conf. on Cybernetics and Society, Denver, CO, USA, 8-10 oct. 1979 (New York, USA: IEEE 1979) p. 621-624.

2. E. Panarella, Found. Phys. 4, 227(1974).

3. A. L. de Brito and A. Jabs, Can. J. Phys. to be published.

4. V. F. Weisskopf and E.P. Wigner, Z. Phys. 63, 54(1930); H. Haken: Laser Theory, Springer Berlin (1970) (Encyclopedia of Physics, Vol. 25/5c) p. 131.

5. M. Abramowitz, I. Stegun (eds.): Handbook of Mathematical Functions, Dover, New York (1965), p. 232.

6. G.S. Voronov, G.A.Delone, and N.B. Delone, Soviet Physics JETP, 24, 1122(1967).

7. G.S. Voronov and N.B. Delone, Soviet Physics JETP, 23, 54(1966).

8. G.S. Voronov, G.A. Delone and N.B. Delone, JETP Letters 3, 480(1966), transl. p. 313.

9. P. Belland, C. De Michelis and M. Mottioli, Optics Comm., 4, 50(1971).

10. A.F. Haught, R.G. Meyerand Jr., D.C. Smith, in: P.L. Kelly, B. Lax, P.E. Tannenwald (eds.), Physics of Quantum Electronics, Mc Graw Hill, New York (1966), p. 509-519.

11. J.R. Wilson, J. Phys. D: Appl. Phys. 3, 2005(1970).

12. C.L.M. Ireland, A.Yi, J.M. Aaron, and C. Grey Morgan, Applied Physics Letters, 24, 175(1974).

13. P. Agostini, G. Barjot, G. Mainfray, C. Manus, and J. Thebault, IEEE Journal of Quantum Electronics, QE-6, 782(1970).

14. N.G. Basov, V.A. Boiko, O.N. Krokin, and G.V. Sklizkov, Soviet Physics - Doklady, 12 248(1967).

15. V. Chalmeton, Le Journal de Physique 30, 687(1969).

16. A.J. Alcock, K. Kato and M.C. Richardson, Optics Comm., 6, 342(1972).

17. F.V. Bunkin, I.K. Krasyuk, V.M. Marchenko, P.P. Pashinin, and A.M. Prokorov, Soviet Physics JETP, 33, 717(1971).

18. N.S. Kopeika and A.P. Krushelevsky, Appl. Optics, 17, 3933(1978).

19. A.J. Alcock, C. DeMichelis and M.C. Richardson, IEEE Journal of Quantum Electronics, QE-6, 622(1970).

20. C.H. Chan, C. D. Moody and W.B. McKnigt, J. Appl. Phys. 44, 1179(1973).

21. D. Held. G. Mainfray, C. Manus, J. Morellec, in: Proc. 10th Int. Conf. on Phenomena in Ionized Gases, Oxford, England, September 13-18, 1971, p. 45; Phys. Letters 35A, 257 (1971).

CAPTIONS

FIG. 1. Sketch of the line broadening by focalization.

TABLE I. Values of N x Q for the exponentially damped Lorentzian with $\varepsilon = 0.2$, $\chi = 18.8$, using the experimental data (6-13), in formulas [5], [8] and [9].